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Research Paper

Viscosity estimation and component identification for an oil-water emulsion with the inversion method

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HIGHLIGHTS

- A method of viscosity estimation for an oil-water emulsion is proposed.
- The method can also be used to identify the components of an oil-water emulsion.
- Inversion accuracy of the ingredients can satisfy the engineering applications.
- Results can also meet the need of real-time online measurement.

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ABSTRACT

A method based on inverse problem theory for estimating the viscosity and composition of oil-water emulsions is proposed. By establishing a novel convective heat transfer model for non-Newtonian fluids, the temperature field of an oil-water emulsion is obtained. An optimal estimation of the apparent viscosity of the mixture can be obtained by determining the relationship between the temperature field and apparent viscosity. Based on this estimation, to obtain the concentration of an oil-water mixture, a prediction model indicating the relationship between the viscosity and emulsion composition is established. Experiments were carried out to validate this method for oil-water pipe flow. Light crude oil, heavy crude oil, and hydraulic oil were considered for this validation. Comparisons between the estimated values and experimental data showed that this method was reliable for predicting the compositions of oil-water emulsions with a high water content or high oil content. The absolute error of the composition predictions for light crude oil and hydraulic oil emulsions was no more than 8%, which indicated the validity of the proposed method.

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1. Introduction

Oil-water emulsion is prepared when one liquid is dispersed as droplets in another immiscible liquid. These emulsions include oil-in-water (O/W) and water-in-oil (W/O) emulsions [1,2]. Nearly 80% of worldwide crude oil is produced in the form of oil-water emulsions. Crude oil emulsions often form due to turbulent mixing and intense stirring during oil exploitation and transportation. As the water content increases, crude oil and water are mixed by mechanical equipment and form emulsions. Most of these extraction liquid emulsions are W/O type emulsions, whereas in the high water cut stage or in secondary oil recovery, most extraction liquids are O/W type emulsions [3].

The viscosity of oil-water emulsions is an important parameter in oil field operations. Since the introduction of the empirical formula of the apparent viscosity of dilute solid particles dispersed in a mixture by Einstein in 1906 [4], researchers have developed a large number of models and empirical or semi-empirical formulas for predicting the viscosity of oil-water emulsions. At present, most emulsion viscosity calculation models are based on the Taylor [5], Richardson [6], Pal and Rhodes [7] or Pal [8] models. The Taylor model assumes spherical liquid drops and is suitable for emulsions with very low internal phase concentration. The Richardson model uses an exponential function to describe the volume fraction of the dispersed phase. The Pal and Rhodes model assumes non-Newtonian behavior in high concentration emulsions and accounts for dispersed droplet flocculation and hydration effects. The Pal model primarily considers the influence of the shear rate on emulsions and claims that there is a large difference between mixed viscosities of emulsion systems. However, most of the existing

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Nomenclature

a	thermal diffusivity, m^2/s
C_p	heat capacity at constant pressure, $J/(kg \cdot {}^\circ C)$
J	Jacobian matrix of the parameters, dimensionless
K	consistency coefficient, dimensionless
L	the heating length, m
n	the rheological index of the power-law fluid, dimensionless
P	certain coefficients for the thermal properties, dimensionless
P_0	initial value of the thermal property parameter, dimensionless
Pr	Prandtl number, dimensionless
p	pressure, Pa
R	the inner radius of the heat transfer pipe, m
Re	Reynolds number, dimensionless
r	radial distance, m
S	L-M method error, dimensionless
T	temperature, K
$T_{num}(P)$	temperature field that is be calculated, K
T_{exp}	experimental data of temperature, K
T_w	outside wall temperature, K
U	the parameter of the viscosity coefficient, dimensionless
u	the axial velocity, m/s

Greek letters

γ	shearing rate, s^{-1}
ε	setting error, dimensionless
ε_c	volume content of the continuous phase, dimensionless
λ	coefficient of the heat conductivity, $W/(m \cdot K)$
λ_m	emulsion conductivity, $W/(m \cdot K)$
μ	the viscosity coefficient, Pa·s
μ_{LM}	iteration parameter of the L-M method, dimensionless
μ_c	viscosity of the continuous phase, Pa·s
μ_d	viscosity of the dispersed phase, Pa·s
μ_e	emulsion viscosity, Pa·s
ρ	density, kg/m^3
τ	shear stress, Pa
φ	volume content of the dispersed phase, dimensionless

Superscripts

K	algorithm step

viscosity prediction models for emulsions are restricted to Newtonian emulsions. Only the Pal and Rhodes model considers the effects of non-Newtonian behavior. Most of the current methods for predicting viscosity are based on experimental data and empirical formulas. Their applications also require large amounts of experimental data. Thus, there is a need for a viscosity prediction method that is widely applicable to oil water emulsions.

Composition detection technology of oil water mixtures is another key technology that is used in the separation of oil and water in petroleum transportation and chemical engineering systems. Current methods for the identification of mixture components, such as infrared absorption spectrometry [9], γ-ray attenuation [10], and microwave [11], can achieve higher measurement accuracy, but have defects, such as high equipment cost and complex operation procedures. Furthermore, the biggest drawback of these methods is that they are difficult to carry out for on-line monitoring of oil-water mixtures.

Modeling of the inverse heat transfer problem (IHTP) provides an effective way to predict the viscosity and composition of oil-water emulsions. IHTP measures the time-varying temperature of points within the boundary of an object using experimental methods. The parameters of the heat flux of the object, thermophysical properties of the material and distribution of the heat source can be obtained by solving the resultant heat transfer differential equations [12]. IHTP is divided into three types based on the characteristics of the inversion parameters: a heat source identification inverse problem, a thermal properties identification inverse problem and a boundary conditions identification inverse problem [13]. In recent years, research on the inverse problem has rapidly developed in thermodynamic system state monitoring and reconstruction [14], thermal process control [15], and thermal property identification [16]. However, inverse problem technology has not been applied to predict the viscosity and components of oil-water emulsions.

To estimate the viscosity and composition of oil-water emulsions in a device, a heat transfer model of the non-Newtonian fluid is first established based on the flow state. The viscosity coefficient of the fluid mixture is then estimated using the Levenberg-Marquardt (L-M) method. By establishing a relationship between the viscosity and composition of the oil-water mixture, estimated values of the components are obtained. After validation, the method proposed herein guarantees higher accuracy in predicting the viscosity and composition of oil-water emulsions.

2. Theoretical study

2.1. Description of the direct problem

During petroleum transportation, most thermodynamic processes occur in the pipe section, such as heat transfer in high viscosity crude oil. Research on pipe flow has been performed for several centuries, among which the most developed model is for circular pipe flow [17]. Therefore, a circular tube convection heat transfer model was chosen as the theoretical model. Furthermore, oil-water emulsions were considered power law fluids [18], which shows the characteristics of non-Newtonian fluids.

There are several radial temperature differences and axial temperature drops in crude oil pipes. The physical properties (especially viscosity) of crude oil depend on temperature, which requires the simultaneous consideration of the conservation of momentum and energy to describe heat convection. Herein, crude oil flow in pipes were considered at steady state.

2.1.1. Physical model

Ignoring gravity and the body force and assuming fully developed horizontal pipe flow and steady state conditions throughout the system, fluid flow velocity only occurs in the axial direction. A physical model was established as follows (Fig. 1).

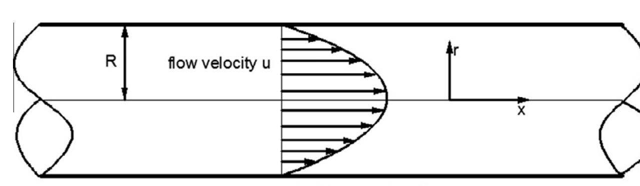

Fig. 1. Convective heat transfer model diagram.

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